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FOR THE COMMANDER

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A DESIGN FOR AN ELECTRO-OPTIC IMPLEMENTATION OF A WIDEBAND NULLING SYSTEM

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ABSTRACT

A wideband nulling antenna system is difficult to build with RF and IF microwave components. The main obstacle to achieving deep, wideband (≥ 1 GHz) nulls is the necessity for extremely accurate channel tracking over the large percentage bandwidth by many components in the receiver chain. Inadequate channel tracking between any two parallel components in the chain could severely degrade the overall nulling performance.

Recent advances in optical technology hold the realistic prospect of alleviating much of the channel tracking problem, as well as potentially providing the secondary benefits of reduced weight and volume. Once the RF signal is converted to an optical frequency, the minute percentage bandwidth occupied by the signal should make channel tracking of the subsequent optical components a relatively easy task.

This report proposes an electro-optical implementation of a wideband nulling antenna system. It is shown that all the required components of an optical nuller are within the current state of the art. The chosen electro-optical devices have no inherent limitation that will prevent their being used in a direct RF-to-optical implementation at frequencies up to and including the EHF band.

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1. INTRODUCTION

A wideband nulling antenna system is difficult to build with RF and IF microwave components. The main obstacle to achieving deep wideband ($>$ 1 GHz) nulls is the necessity for extremely accurate channel tracking by many components in the receiver chain over the large percentage bandwidth. Inadequate channel tracking between any two parallel components in the chain could severely degrade the overall nulling performance.

Recent advances in optical technology hold the realistic prospect of alleviating much of the channel tracking problem, as well as potentially providing the secondary benefits of reduced weight and volume. Once the RF signal is converted to an optical frequency, the minute percentage bandwidth occupied by the signal should make channel tracking of the subsequent optical components a relatively easy task.

This report presents a design for an optical implementation of a wideband multibeam nulling antenna system. The basic optical design, which consists of various electro-optical devices connected by optical fibers, may be used in either an IF-to-optical or an RF-to-optical implementation. All the required optical components are either within or slightly beyond the current state of the art. In addition, the chosen optical devices have no inherent limitation that will prevent their being upgraded in several years to allow operation at frequencies well into the EHF range.

2. SYSTEM GOALS

The following specific goals are set for the nulling antenna: a bandwidth of 2 GHz, a system noise figure of 6.5 dB, null depths of 40 dB, and a dynamic range of 40 dB. To avoid extraneous consumption of the nuller's degrees of freedom, the intermodulation (IM) level should be no more than −40 dBc. The graph of the null-depth requirement in Figure 1 shows the extremely close channel-to-channel tracking that is necessary, on the order of 0.5° in phase and 0.1 dB in amplitude. The fewer components there are in series in each channel, the easier it is to achieve the required channel tracking. This is the primary reasoning for considering the replacement of many of the system's components with optical devices.

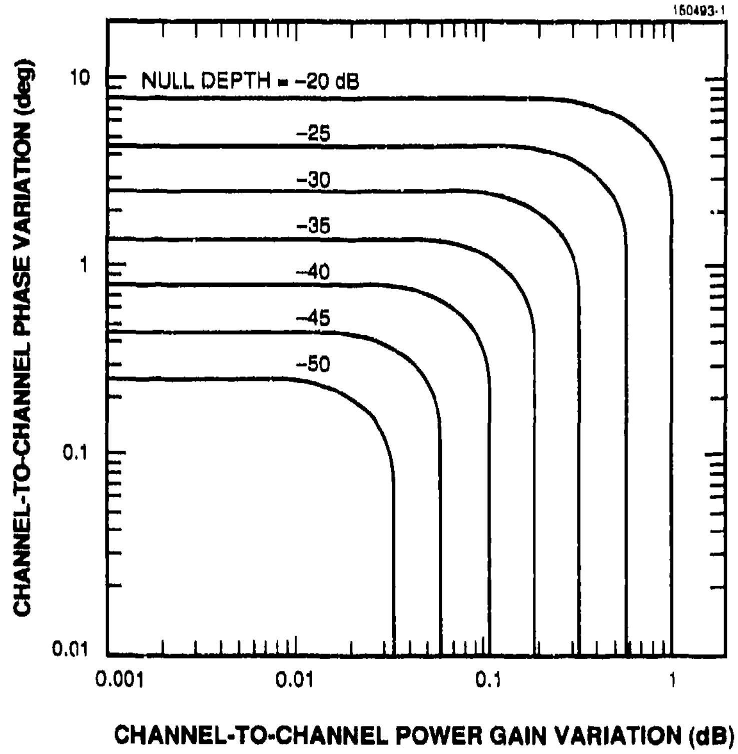

Figure 1. Channel tracking requirements for a given nulling depth.

Due to the very small ratio of the signal bandwidth to the optical carrier frequency, the channel tracking error of the optical subsystem should be negligible. Indeed, if the optical subsystem extends to the point where the weighted channels are combined, only the components up to and including the RF/optical interface need to be carefully matched. Table 1 itemizes the matched devices required per channel for each of several system designs[1]: a microwave system with a downconversion to an intermediate frequency (IF); a microwave system at RF; a scheme involving downconversion to IF, followed by upconversion to optical frequencies; and a design based on direct RF-to-optical conversion.

TABLE 1

Number of Matched Devices per Channel

	Microwave		Optical	
Unit	**IF**	**RF**	**IF**	**RF**
LNA	1	1	1	1
Mixer	1	0	1	0
IF amp	1	0	1	0
Modulator	0	0	1	1
Switches	2–6	2–6	0	0
Splitter	1	1	0	0
Attenuators	2	2	0	0
Summer	1	1	0	0
Total	9–13	7–11	4	2

Table 1 indicates that the use of an optical subsystem engenders a reduction of about 55 to 80% in the number of devices that must be carefully matched. Because the total channel tracking error budget is shared by all the components in each channel, the fewer the components that need to be matched, the greater the error budget that can be allocated to each individual element. Consequently, a given broadband null depth should be easier to achieve using at least a partially optical implementation.

[1]The accounting used in Table 1 is based on high-level system components. Consideration of the numerous subcomponents would accentuate the table's numerical distinction between the microwave and optical designs.

3. OPTICAL NULLING SYSTEM DESIGN

3.1 IF/Optical Nulling Implementation

The optical implementation of a modified Applebaum-Howells nuller, outlined in Figure 2, takes the form of various guided wave electro-optic (EO) devices connected by optical fibers. As an example, the devices can be constructed of Ti:LiNbO$_3$; that is, they can be based on titanium waveguides diffused into a lithium niobate substrate.

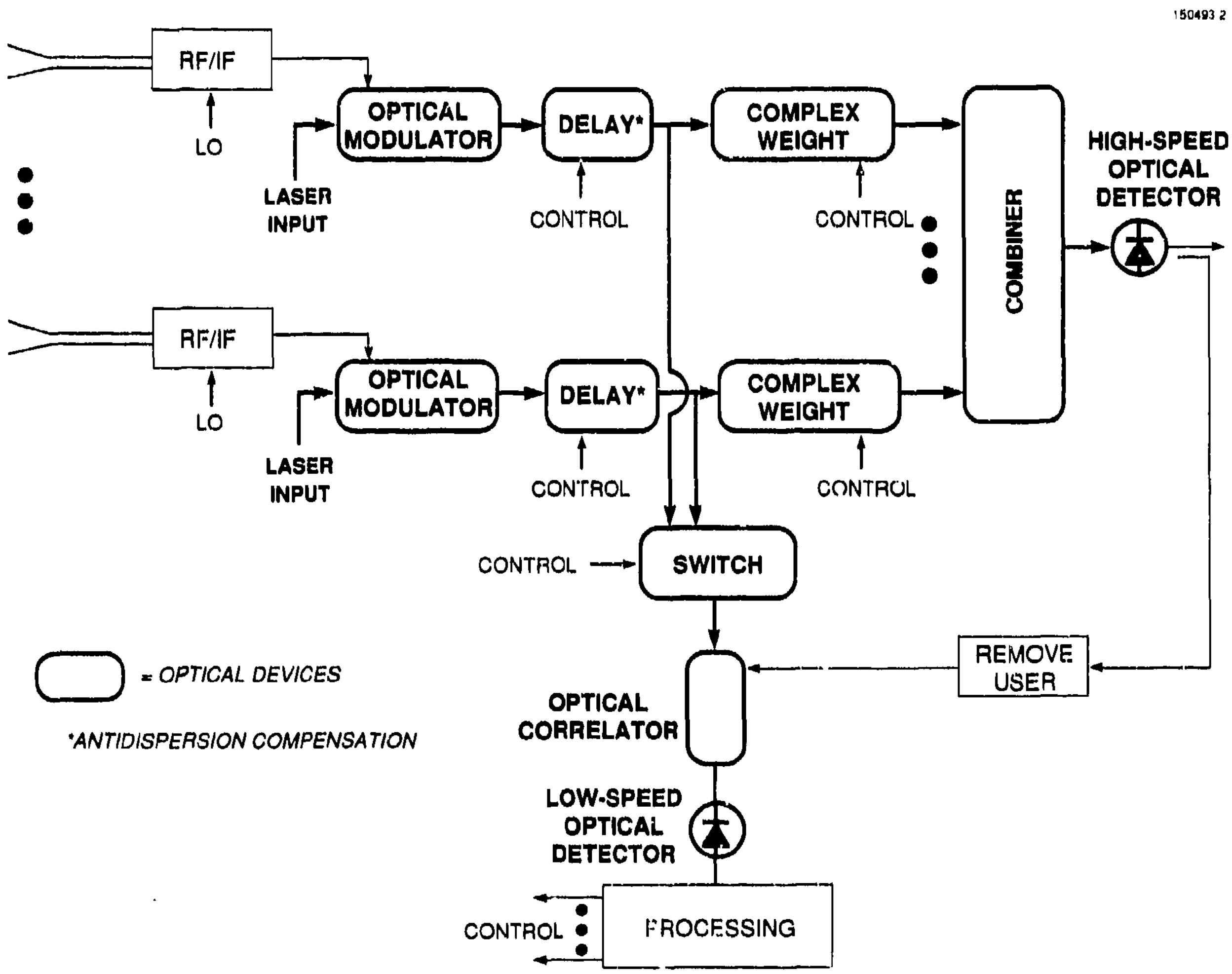

Figure 2. IF/optical nulling system.

Guided-wave optics has a number of clear advantages over bulk optics: smaller size and weight, easier optical alignment, and relative insensitivity to environmental conditions. The choice of EO as opposed to acousto-optic (AO) devices was motivated mainly by the latter's bandwidth limitations (see Appendix A).

Referring to the figure, the operation of the system is as follows. After undergoing downconversion and amplification in the RF/IF stages, the signals from the antenna elements are used to externally modulate the optical beams generated by separate low-noise lasers. External modulation was chosen over direct laser modulation because the former has a greater bandwidth and is more tolerant of temperature fluctuations. The modulators and the optical correlators are electro-optic Mach-Zehnder (MZ) devices operated in their linear mode (see Appendix A).

The signal-modulated optical beams are then routed through switchable delay lines, which compensate for the antenna dispersion. Nulling is accomplished by the weighting and combining of the all the channels' optical beams. (Possible designs of the EO delays and complex weights are discussed in Appendices B and C, respectively.) Optical detection of the combiner's output produces the final output signal, a portion of which is fed back to be correlated with the input signal.

Correlation of the output signal (with the desired communications signal removed) and the raw signal is required of the Applebaum-Howells algorithm [1]. Once the desired signal is removed (to avoid nulling it), the resulting feedback signal is offset in frequency and used to modulate a second linearly biased MZ device. Together with the previous MZ modulator and the subsequent low-speed optical detector, this MZ performs the required correlation (see Appendix A). If the integration time constant of the detector is too short, it can be easily increased by the addition of a low-pass filter or an integrator to the detector's output.

In the design shown in Figure 2, the optical correlator and the low-speed optical detector are time-division shared by all the channels, thereby requiring the optical switch shown. If a correlator/detector pair were assigned to each channel, the switch would be superfluous. A possible variation of the IF/optical design is to separate the phase and amplitude weighting by replacing the complex weight with an amplitude weight and including the phase weight as part of the local oscillator control at the front end of the receiver. The purpose of such a separation would be to simplify the form of the optical weight, thereby decreasing its optical loss by about 2.5 dB.

For this nuller design, channel tracking is critical only up to and including the electrical interface of the initial MZ modulator. That is, great care must be taken to match the antenna circuits, the RF/IF modules, and the microwave interface of the first MZ. The channel tracking of the other optical components will be virtually guaranteed by the small percentage bandwidth occupied by the signal.

3.2 RF/Optical Nulling Implementation

Figure 2 can also be taken to illustrate the RF/optical system configuration if the local oscillators are deleted and the RF/IF stages are replaced by low-noise amplifiers. The opportunity afforded by downconversion to separate the phase and amplitude portions of the complex weight is, of course, unavailable at RF, thereby necessitating the use of a complete electro-optic complex weight.

Because external modulation is being used, the lasers for the RF system can be the same as those in the IF system. On the other hand, the MZ modulators and the output photodetector need to have their operating ranges extended to encompass the RF signal band. In recent years, photodetectors operating up to 100 GHz have been built, while 40-GHz MZ and coupler optical modulators have been tested [2,3]. Therefore, this RF/optical system design is valid for signal frequencies well into the EHF range. As explained in Section 4, nulling performance similar to that of the IF configuration should be achievable.

4. SYSTEM LINK BUDGET

Table 2 details the system constants and variables necessary for the link budget calculation of an IF nulling implementation, with a 2-GHz bandwidth centered at 6 GHz, and using laser wavelengths of 1.3 μm. The interconnections between the optical devices are by means of optical fibers, which, at the modest lengths required, have negligible losses other than at their interfaces. As is evident from the table, state-of-the-art technology is assumed in the device-to-fiber interface losses, the laser relative intensity noise (RIN) level, and in the effective receiver noise current that characterizes the optical detector performance.

The calculation itself is detailed in Table 3. In making the calculation, the RF/IF amplifier gain (G_{RF}) was set to 33.5 dB, the maximum value that maintains the third-order intermodulation of the front end MZ at -40 dBc. It was found that the system goals (of 6.5-dB NF, 40-dB dynamic range, and -40-dBc IM) could be satisfied by a laser power of 17.5 dBm.

To allow easy calculation of how system parameters are affected by the laser power level, graphs of the output signal and noise terms and the system figures of merit are given in Figures 3 and 4, respectively. Note that in the performance region of interest, the dominant noise terms are the shot noise and the modulator thermal noise. (The latter term is due to the modulation of the first MZ by the thermal noise of the RF front end.) This is in contrast to typical well-designed optical links, which are solely limited by shot noise.

For nulling at RF, the link calculation is similar. Assuming the MZ and detector implementation losses are the same, the only differences are a lower MZ modulation response (which decreases approximately linearly as a function of frequency) and a correspondingly higher RF amplifier gain. With these modifications, performance nearly identical to that of the IF system should be obtainable.

TABLE 2

System Constants and Variables

Item	Symbol	Value
Electron charge	e	1.6×10^{-19} C
Boltzmann's constant	k	1.38×10^{-23} J/K
Ambient temperature	T_0	290 K
Bandwidth	B_N	2 GHz
MZ 3rd-order IM depth	M_I	2.83
Termination resistance	R_D	50 Ω
RF power at antenna	P_{ant}	–29 dBm
Antenna circuit loss	L_{ant}	–1 dB
RF/IF amplifier gain	G_{RF}	33.5 dB
RF/IF noise figure	F_{RF}	3.5 dB
MZ modulation response	K	35 W^{-1}
Laser power	P_L	17.5 dBm
Laser RIN	r^2	–170 dB/Hz
Laser/fiber interface loss	L_1	–1 dB
Fiber/MZ interface loss	L_2	–0.5 dB
MZ implementation loss	L_3	–1 dB
MZ linear-bias loss	L_4	–3 dB
MZ/fiber interface loss	L_5	–0.5 dB
Fiber/delay interface loss	L_6	–0.5 dB
Delay implementation loss	L_7	– 2 dB
Delay/fiber interface loss	L_8	–0.5 dB
Fiber/weight interface loss	L_9	–0.5 dB
Weight implementation loss	L_{10}	–3.5 dB
Weight/fiber interface loss	L_{11}	–0.5 dB
Fiber/combiner interface loss	L_{12}	–0.1 dB
Combining loss	L_{13}	–0.8 dB
Fiber/detector interface loss	L_{14}	–0.5 dB
Detector responsitivity	D	0.8 A/W
Detector dark current	i_D	1 pA
Receiver noise current	i_{det}	5 pA/$\sqrt{Hz}$

TABLE 3

System Link Budget Calculations

System Factor	Symbol	Formula	Value
RF input power at MZ	P_{in}	$P_{ant} \cdot L_{ant} \cdot G_{RF}$	3.5 dBm
Noise at MZ input	n_{MZ}	$G_{RF}\,(kT_0B_N)\,(L_{ant}+F_{RF}-1)$	-44.4 dBm
MZ modulation depth	m	$\sqrt{P_{in} \cdot K}$	0.28
Total optical loss	L_{opt}	$\prod_{i=1}^{14} L_i$	-14.9 dB
Optical power at MZ	P_{MZ}	$P_L \cdot L_1 \cdot L_2$	16 dBm
Optical power at detector	P_{det}	$P_L \cdot L_{opt}$	2.7 dBm
Bias current	i_B	$P_L \cdot L_{opt} \cdot D$	1.5 mA
RF gain via optics	G	$\frac{1}{2} \cdot i_B^2 \cdot R_D \cdot K$	-27.2 dB
Shot noise	n_{shot}	$2e \cdot (i_B + i_D) \cdot R_D \cdot B_N$	-73.3 dBm
RIN noise	n_{RIN}	$r^2 \cdot i_B^2\,(1+m^2/2) \cdot R_D \cdot B_N$	- 86.5 dBm
Detector thermal noise	n_{det}	$i_{det}^2 \cdot R_D \cdot B_N$	-86.0 dBm
Modulator thermal noise	n_{mod}	$G \cdot n_{MZ}$	-71.6 dBm
Total output noise	n_{total}	$n_{shot} + n_{RIN} + n_{det} + n_{mod}$	-69.2 dBm
RF signal output	S	$G \cdot P_{in}$	-23.7 dBm
3rd-order output intercept	I_3	$\frac{1}{2} \cdot M_I^2 \cdot i_B^2 \cdot R_D$	-3.6 dBm
3rd-order IM output	I	$S^3/\,(I_3)^2$	-63.9 dBm
Output SNR	SNR	S/n_{total}	45.5 dB
Excess noise of optics	$n_{e,o}$	$n_{shot} + n_{RIN} + n_{det}$	-72.9 dBm
Relative optics noise	n_{rel}	$n_{e,o}/\,(kT_0B_N)$	8.1 dB
Optics noise figure	F_o	$(n_{rel})\,/G+1$	35.3 dB
Receiver noise figure	F_r	$(F_o-1)\,/G_{RF}+F_{RF}$	5.8 dB
System noise figure	F_s	$(F_r-1)\,/L_{ant}+1$	6.4 dB
MZ dynamic range	ΔR	$(I_3/n_{total})^{2/3}$	43.7 dB
Relative 3rd-order IM level	I_{rel}	I/S	-40.2 dBc

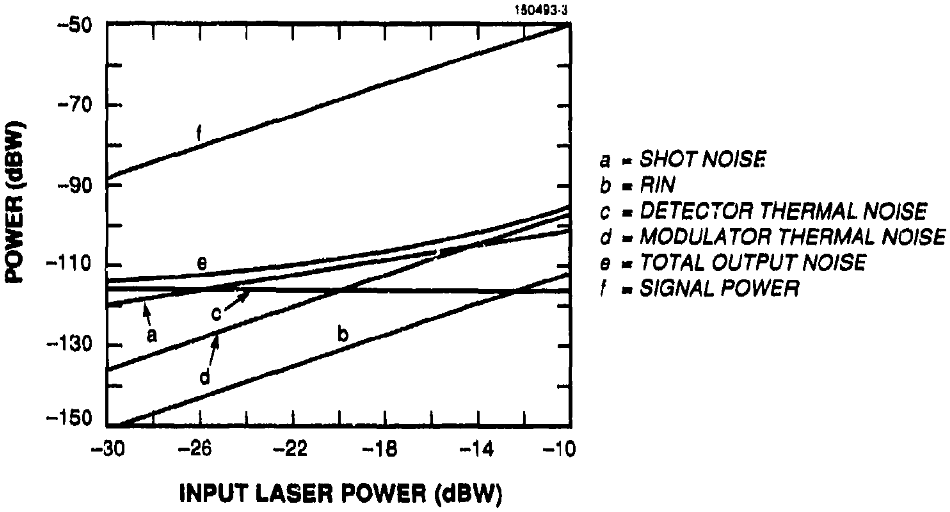

Figure 3. Output RF power terms versus laser power.

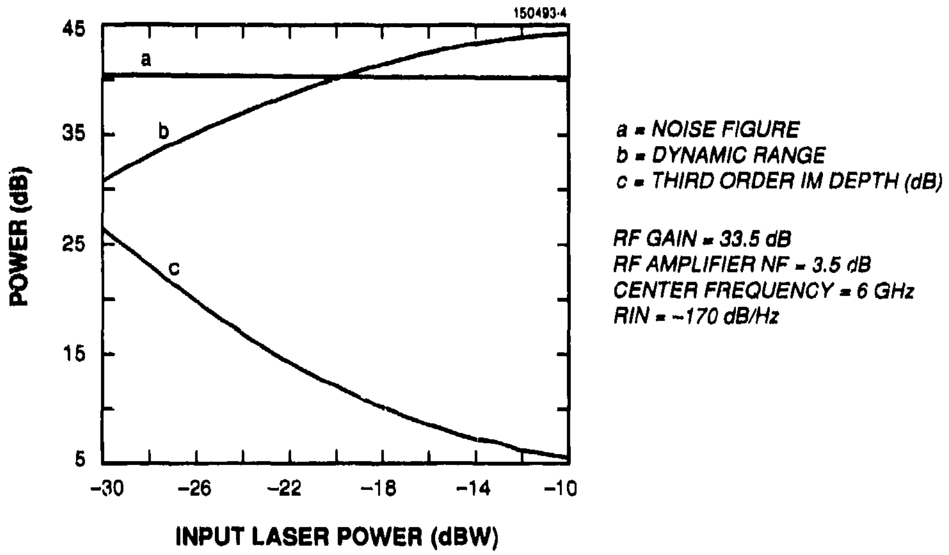

Figure 4. System figures of merit versus laser power.

5. CONCLUSION

An electro-optical design of a wideband (2-GHz bandwidth) nulling antenna system has been proposed, both in the form of an IF/optical system and an RF/optical system. The use of optical subsystems alleviates much of the stringency of the overall system channel tracking requirements. Assuming state-of-the-art components and procedures, a detailed link budget was presented. It indicates the feasibility of the optical subsystem achieving a performance level that is consistent with overall system specifications of a 40-dB null depth and a 6.5-dB noise figure.

By using appropriate electro-optical implementations of the necessary nuller components (correlators, switchable delay lines, weights, etc.), the proposed nulling system could operate over multi-GHz bandwidths centered at frequencies well into the EHF band.

APPENDIX A
WIDEBAND ELECTRO-OPTIC CORRELATORS

Previous optical implementations of correlators have used AO devices, namely Bragg cells [4]. These AO implementations could be in the form of either bulk devices and lenses [5] or, more recently, waveguide Bragg cells (i.e., surface acoustic wave devices) and waveguide lenses integrated on a single chip [6]. In either case, whether they are bulk or waveguide, AO devices are innately limited to operating at frequencies below ~6 GHz [7]. For correlator applications involving higher frequencies, using acousto-optics would necessitate translating the signals to an IF below 6 GHz. On the other hand, since it is known that waveguide EO devices can operate at much higher frequencies (beyond 40 GHz [3]), an EO correlator could be used directly.

This appendix presents a design for an EO time integrating correlator that consists of the successive modulation of a guided lightwave's intensity by each of the two signals to be correlated and the subsequent detection of the resulting lightwave by a photodetector of appropriate bandwidth. The correlator can be implemented using electro-optic MZ modulators, thereby allowing operation well into the EHF frequency range [3].

A.1 Mach-Zehnder Modulator

Figure A-1 illustrates a commonly used configuration of an electro-optic MZ modulator. It is easy to show that the input and output intensities are related by

$$I_{out} = I_{in}\left[\gamma + (1-\gamma)\cos\phi\right] \quad , \tag{A.1}$$

where ϕ is the relative phase shift and γ is a factor depending on the ratio of the optical powers of the paths. For an equal power split, $\gamma = \frac{1}{2}$ and (A.1) takes on the more familiar form [8,9]

$$I_{out} = \frac{I_{in}}{2}\left(1 + \cos\phi\right) \quad . \tag{A.2}$$

When it is appropriately biased, the modulator becomes linear for small enough signals:

$$\begin{aligned} I_{out} &= \frac{I_{in}}{2}\left(1 + \sin\phi\right) \\ &\approx \frac{I_{in}}{2}\left(1 + kV\right) \quad , \end{aligned} \tag{A.3}$$

where V is the modulating voltage and k is a proportionality factor [9].

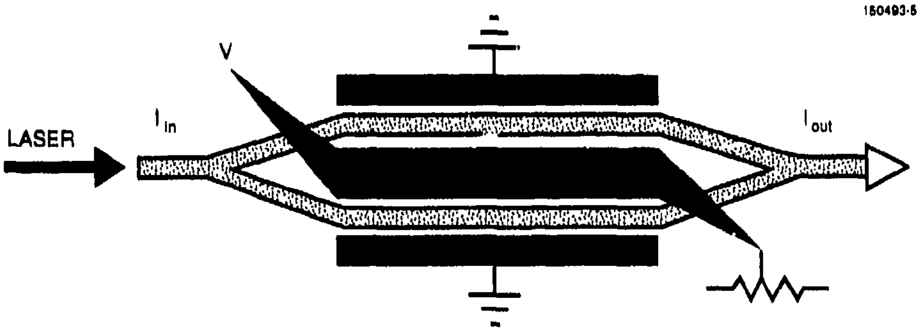

Figure A-1. Electro-optic Mach-Zehnder modulator.

A.2 Mach-Zehnder Correlator

The proposed correlator is formed by placing two MZs in serics, followed by a photodetector, as shown in Figure A-2. Biasing both MZs to be linear, one can then show, by proceeding in a manner similar to that of Section A.2, that

$$I_{out} = \frac{I_{in}}{4}(1 + kV_1)(1 + kV_2) \quad . \tag{A.4}$$

[Though Equation (A.4) is based on the assumption of equal-power splits at the input of each MZ, this assumption is unnecessary for the correlator's operation. Unequal splits would simply introduce different constants of proportionality and reduce the dynamic range.]

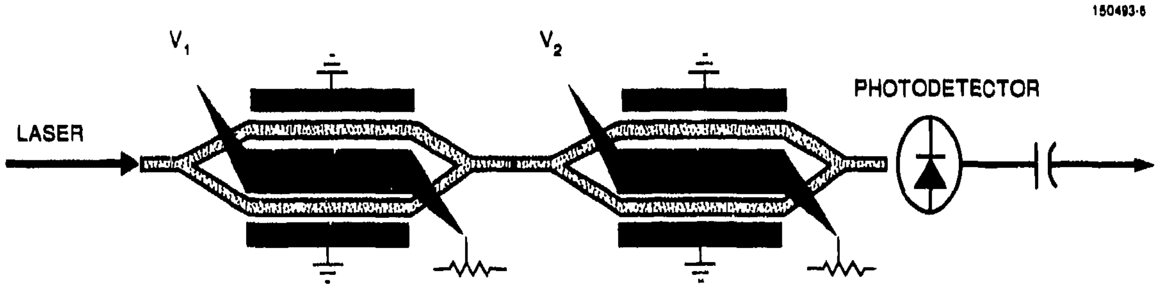

Figure A-2. Electro-optic Mach-Zehnder correlator.

Assuming the signals V_1 and V_2 have (different) center frequencies of ω_1 and ω_2, respectively, the input to the photodetector can be decomposed into five terms, each at a different frequency. These are the bias term at DC, the V_1 term at ω_1, the V_2 term at ω_2, and the V_1V_2 terms at $|\omega_1 \pm \omega_2|$. If the bandwidth B of the photodetector is chosen such that

$$|\omega_1 - \omega_2| < B < \min\{\omega_1, \omega_2\} \quad , \tag{A.5}$$

then its output will feature only the DC term plus the V_1V_2 difference-frequency term. Once the DC term is blocked, the resulting crossterm can be further integrated to form the desired correlation.

For this correlator to work, it is important to offset the center frequency of one signal relative to the other. Without this simple step, the only available multiplicative term would be at the sum frequency, needlessly complicating the photodetector and the circuitry that follows.

The correlator design is based on the MZ modulator, though any electro-optic modulator operating in a linear regime would serve as well. The bandwidth of the signals that can be correlated is limited solely by the speed of the modulators.

APPENDIX B
OPTICAL FAST-SWITCHING DELAY LINES

Figure B-1 illustrates how low-loss, fast-switching delays may be constructed electro-optically. Essentially, they consist of two sets of directional-coupler switches separated by a set of fibers of various lengths.

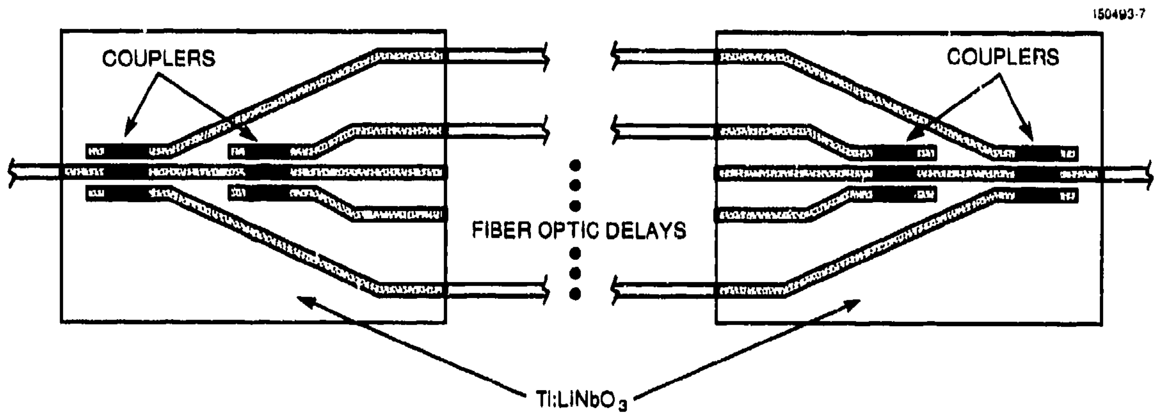

Figure B-1. Optical fast-switching delay lines.

The optical signal is routed to the first N-way switch, which is connected to the second N-way switch by N fibers. The lengths of the interconnecting fibers are selected so as to form the desired set of delays, taking into account the different on-chip delays for each of the switch settings. Of the N switches on each chip, only one is activated at any given time. Coupled with the linear arrangement of the switches on the chip, this avoids the chain of optical losses that would be seen in a more typical logarithmic arrangement, at the expense of more switches (N as opposed to $\log N$).

The total optical loss of this delay line design should be about 2 dB: 0.5 dB at each of the two internal fiber/device interfaces, plus 0.5 dB for each of the two N-way switches. Essentially no attenuation is introduced by the short lengths of fiber used as delays. To ensure 40 dB of electrical isolation, each of the switches must be manufactured to yield 10 dB of optical isolation, a relatively easy task.

APPENDIX C
ELECTRO-OPTICAL COMPLEX WEIGHT

A possible design for an EO complex weight is shown in Figure C-1.[2] Both the amplitude weighting, by means of a directional-coupler modulator, and the phase control, whereby the optical power is distributed to one or two of four waveguides, are performed on a Ti:LiNbO$_3$ chip. Each of the waveguides is connected to one of four fibers, the lengths of which serve to produce relative microwave delays of 0°, 90°, 180°, and 270°. The four single-mode fibers are merged into one multimode fiber by means of a fused coupler. (Thus, the input of the complex weight is single mode, but its output is multimode.) An arbitrary phase weight can be generated by the appropriate setting of the phase-control couplers.

The switching capabilities of the EO complex weights, as well as of the delays described in Appendix B, are orders of magnitude greater than are likely to be required.

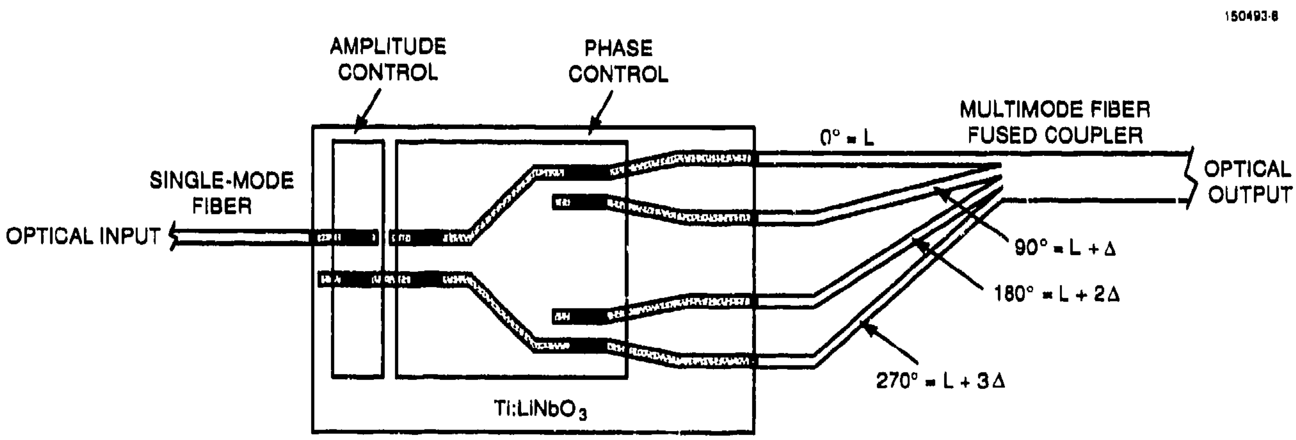

Figure C-1. Electro-optical complex weight.

[2]The form of the complex-weight design shown in the figure is due to L.M. Johnson.

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Recent advances in optical technology hold the realistic prospect of alleviating much of the channel-tracking problem, as well as potentially providing the secondary benefits of reduced weight and volume. Once the RF signal is converted to an optical frequency, the minute percentage bandwidth occupied by the signal should make channel tracking of the subsequent optical components a relatively easy task.

This report proposes an electro-optical implementation of a wideband nulling antenna system. It is shown that all the required components of an optical nuller are within the current state of the art. The chosen electro-optical devices have no inherent limitation that will prevent their being used in a direct RF-to-optical implementation at frequencies up to and including the EHF band.

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